# Measurement of the Gerasimov-Drell-Hearn Integral at low $Q^2$ on the Neutron and Deuteron.

A. Deur (Co-spokesperson and contact), V. Dharmawardane,
P. Bosted
Thomas Jefferson National Accelerator Facility

G. Dodge (Co-spokesperson), S. Kuhn
Old Dominion University

D. Crabb, D. Day, R. Lindgren, B. Norum, O.A. Rondon,
K. Slifer (Co-spokesperson), C. Smith, S. Tajima, K. Wang
University of Virginia

K. Griffeon
The College of William and Mary

M. Battaglieri, R. De Vita, M. Ripani
INFN Genova

F. Wesselman
Norfolk State University

and the Hall B Collaboration

27th June 2005

**Abstract**

We propose a precision measurement at low momentum transfer ($0.01 < Q^2 < 0.2$ GeV$^2$) of the Gerasimov-Drell-Hearn integral for the deuteron using the Hall B CLAS detector. By combining these data with the proton data taken under similar conditions (approved E03-006) we can extract the GDH integral on the neutron. These data will provide a benchmark for neutron Chiral Perturbation Theory ($\chi$PT) calculations. Also, at the very low $Q^2$ of the proposed experiment, extrapolation to $Q^2 = 0$ will permit a check of the (real photon) GDH sum rule. Due to the complexity of nuclear medium effects, extraction from both the deuteron and $^3$He is necessary to have confidence in neutron data at very low $Q^2$. An experiment [1] with the same goals as this proposal, but using a $^3$He target was approved in Hall A. In addition, as recently emphasized [2], the GDH sum for the deuteron is a fascinating quantity in its own right and presents a significant test of our present understanding of the properties of few-body nuclei. The experimental conditions will be the same as those of approved experiment E03-006, except for the content of the target cell. The combined data set will therefore provide a self-consistent test of the Bjorken sum, which is believed to be the best quantity to measure in the context of linking the partonic and hadronic descriptions of the strong interaction. To perform this measurement, we request 30 days of beam time.

# Contents

# 1 Introduction

We present here a proposal for measuring the extended Gerasimov-Drell-Hearn (GDH) integral on the neutron and deuteron at low $Q^2$. In the following pages, we first define the GDH sum rule and briefly recall its theoretical basis. After a short review of GDH experimental status, we describe the extension of the GDH integral to finite $Q^2$. Then we discuss the motivations for such a measurement at low $Q^2$. We will end this document describing the proposed measurement and the beam time required to meet our goal.

## 1.1 The Gerasimov-Drell-Hearn Sum Rule

The Gerasimov-Drell-Hearn sum rule for real photon scattering at $Q^2 = 0$ is a fundamental relation that relies on only a few general assumptions:

1. Lorentz and gauge invariance in the form of the low energy theorem of Low [3], Goldman and Goldberger [4].

2. Unitarity in the form of the optical theorem.

3. Causality in the form of an unsubtracted dispersion relation [5] for forward Compton scattering.

For a target of arbitrary spin $\mathcal{S}$, the sum rule [6] reads:

$$\int_{\nu_{th}}^{\infty} \frac{\sigma_P(\nu) - \sigma_A(\nu)}{\nu} d\nu \quad = \quad -4\pi^2 \alpha \, \mathcal{S} \left(\frac{\kappa}{m}\right)^2 \tag{1}$$

where $\sigma_P$ and $\sigma_A$ represent the cross section for photoabsorption with the photon helicity parallel or anti-parallel to the target spin in its maximal state. The integration extends from the onset of the inelastic region, through the entire kinematic range and is weighted by the photon energy $\nu$. $m$ and $\kappa$ represent the target mass and anomalous magnetic moment respectively.

Experimental data and theoretical bounds suggest that the integral converges [7], and the only assumption that might be open to question is the validity of the non-subtraction hypothesis.

Eq. (1) reflects the fact that the presence of an anomalous magnetic moment is a clear signature of internal structure. However, a very small anomalous magnetic moment does not necessarily imply that the particle is nearly point-like. The deuteron, in particular, has quite small $\kappa$ due to the cancellation of proton and neutron anomolous magnetic moments, yet it has a large spatial distribution due to it's relatively small binding energy. If the GDH sum rule holds, than this cancellation must be also reflected in the integral side of eq. (1). Arenhovel *et al.* [8] point out the importance of the threshold photodisintegration channel in satisfying the deuteron GDH sum rule, concluding that the disintegration channel must be approximately equal in magnitude (but opposite in sign) to all other inelastic processes. This strong cancellation is a fascinating feature that demonstrates a subtle connection between the coherent nuclear behaviour at low energy and the incoherent reactions at large energy.

### 1.1.1 Experimental Status

A dedicated test of the GDH sum rule has been undertaken at the MAMI and ELSA facilities, and the combined data set [9, 10] indicates that the proton sum rule is valid to within 10%. Neutron and deuteron data from a polarized $ND_3$ target were also collected by the above collaborations, and analysis is underway. At JLab, an experiment is scheduled in Hall B to measure the (real photon) GDH sum rule for the proton using a frozen spin target [11]. An experiment was approved at SLAC to specifically investigate the convergence of the GDH sum [13] but is not expected to run due to the termination of the SLAC ESA nuclear program. The question of convergence can, however, be addressed in part with the 12 GeV upgrade of JLab.

At very small (but non-zero) momentum transfer, the GDH sum rule can be tested by measuring the $Q^2$-dependence and extrapolating to the real photon point. Hall A experiment E97-110 [1] measured the $Q^2$-dependence of the GDH sum at very low momentum transfer using a polarized $^3$He target. That experiment should shed light on the validity of the GDH sum rule for $^3$He, and also for the neutron provided that the nuclear corrections are under control.

Checking the GDH sum rule for the proton alone is not sufficient to ensure its validity. The low $x$ behavior of the two nucleons may be very different*, which should be considered especially when we realize that the non-subtraction hypothesis is the most questionable assumption in the derivation.

## 1.2 The Extended GDH Sum Rule

Anselmino *et al.* [14] suggested that the GDH integral extended to finite $Q^2$ would illuminate the transition from perturbative to non-perturbative QCD, and pointed out the connection between the extended GDH integral and the Bjorken sum rule [15]. The generalization consists of replacing the photoproduction cross sections of eq. (1) with the corresponding quantities from electroproduction. However, many possible generalizations † exist, depending on the choice of the virtual photon flux, and on the way the spin structure function $g_2$ is included.

Among the different GDH extensions, the one of Ji and Osborn [17] stands out because it generalizes not only the integral side but the full sum rule. Hence, it retains the predictive power that is lost with other definitions. In addition, the same authors showed that the Bjorken and the GDH sum rules are two limiting cases of their generalized GDH sum rule. For an arbitrary hadronic target it is written:

$$\begin{aligned} \overline{S_1}(0,Q^2) &= \frac{8}{Q^2}\int_0^{1-\epsilon} g_1(x,Q^2) \\ &\equiv \frac{8}{Q^2}\overline{\Gamma}_1 \end{aligned} \tag{2}$$

where $g_1$ is the familiar spin structure function and $S_1$ is the forward Compton amplitude. In eq. 2, the overbar represents exclusion of the elastic contribution.

*For example, the low $x$ behaviors of the nucleon spin structure functions $g_1^p$ and $g_1^n$ are known to differ.
†For a review, see [16].

The forward Compton amplitudes are presently calculable using chiral perturbation theory at low $Q^2$, and the higher twist expansion at larger $Q^2$. Eventually, lattice QCD calculations should provide calculations at any $Q^2$. Let us note that moments of the spin structure function are quantities particularly well suited for lattice QCD calculations.

For future reference, we introduce the quantity $I(Q^2)$:

$$I(Q^2) = \frac{2M^2}{Q^2}\Gamma_1(Q^2) \tag{3}$$

which we will refer to as the GDH integral.

#### 1.2.1 Experimental Status

The CERN, SLAC and HERMES collaborations [18, 19, 20] have measured $I(Q^2)$ mainly in the DIS regime for proton, deuterium and $^3$He targets. At JLab, experiment E94-010 measured the GDH integral on the neutron [89] and $^3$He [22] down to $Q^2$ = 0.1 GeV$^2$, while in Hall B, the EG1 collaboration [23, 24, 25] performed similar studies on the proton and deuteron down to $Q^2 = 0.05$ GeV$^2$.

The PAC in recent years has recognized the importance of extending these measurements to the lowest possible $Q^2$, approving E97-110 with A$^-$ rating for 22 days and E03-006 for 20 days with A rating. The Hall A experiment used a $^3$He target down to a momentum transfer of 0.02 GeV$^2$ in order to test $\chi$PT and the GDH sum rule for the neutron and for $^3$He. It is expected that the most difficult part of that analysis will be to understand the nuclear corrections at low $Q^2$ well enough to extract the neutron. In Hall B, experiment E03-006 is scheduled to run in Spring 2006, using a polarized $NH_3$ target down to $Q^2$ = 0.01 GeV$^2$. E03-006 will determine $g_1$ from an absolute (polarized) cross section measurement, thereby eliminating the significant systematic uncertainty that arises from the target dilution factor. To this end, a new Čerenkov counter is being installed in one sector of CLAS to improve the efficiency at small angles. E03-006 will take data at beam energies of 3.2, 2.4, 1.6, and 1.1 GeV, with a short run at 0.8 GeV to study radiative corrections.

The kinematic range of this proposal is where nuclear corrections are expected to be the most difficult. But presently, only $^3$He has been used to access the neutron in this region. For every other region (see table 1), both $^3$He and the deuteron have been utilized to ensure a full understanding of the neutron extraction systematics.

# 2 Motivations

We propose to perform a precision measurement of the GDH integral in the range $0.01 < Q^2 < 0.2$ GeV$^2$, using an $ND_3$ target and the CLAS detector as upgraded for experiment E03-006. Apart from the target, this experiment would have an identical setup and similar beam energy requirements of E03-006. In the following sections we discuss the motivation for performing this experiment.

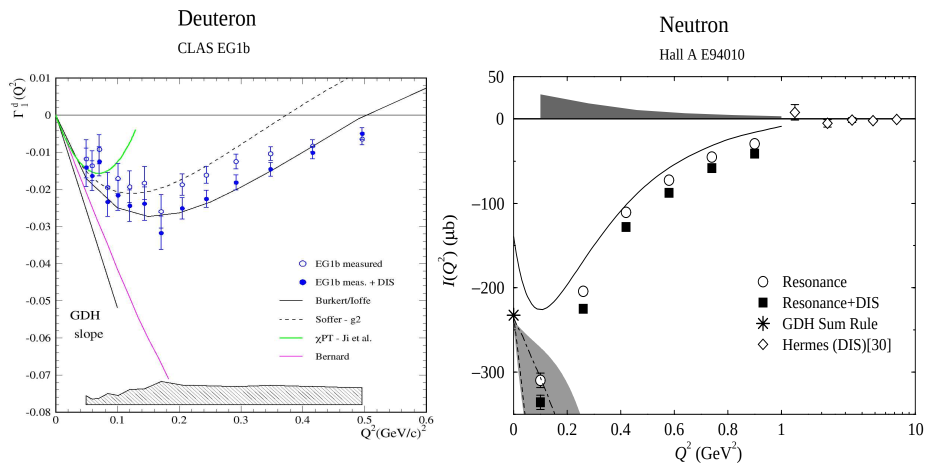


Figure 1: $Q^2$ evolution of the GDH integral on the deuteron and neutron.

## 2.1 The Neutron Extended GDH Sum at Low $Q^2$

The extended GDH sum can be measured and compared to calculations at any $Q^2$. Hence it is a useful quantity for studying the transition from the partonic to hadronic descriptions of the strong interaction. As such, the $Q^2$ dependence of the extended GDH sum has been an important focus of the JLab experimental program [1, 26, 10, 89]. The neutron is particularly important because of the long-standing claim that the GDH sum rule is broken for the neutron, and the access it provides to the Bjorken sum (discussed in section 2.4). As discussed in section 1.1.1, the verification of the sum rule on proton does not preclude its violation for a neutron target.

The low-$Q^2$ domain for the neutron is under investigation at JLab (via $^3$He) [1]. However, the neutron extraction at low $Q^2$ is complicated due to the increasing importance of nuclear effects [28, 8]. An experiment using another target for which the nuclear corrections, and the related systematic uncertainties, are completely different is crucial to establish confidence in the existing neutron results. In appendix A, we recall the procedures used for neutron extraction in the DIS region and, for integrated quantities, in the intermediate $Q^2$ domain. To summarize the appendix, the extraction of neutron moments can be performed with a PWIA method (convolution model), which can be approximated to a good level by the DIS method accounting simply for the effective polarization of the nucleons within the nucleus. The magnitude of the correction grows at low $Q^2$, where there is no further justification of the use of effective polarizations beside the fact that the results are close to the PWIA method. Since PWIA is known to be unreliable at low $Q^2$, both the convolution model and the effective polarization methods cannot be used *a priori* at low $Q^2$. More sophisticated models or calculations have to be used that account for nuclear effects, such as final state interactions, meson exchange currents, EMC effects or Pauli-blocking. Work is on going to include final state interactions that are believed to be the most important at low $Q^2$ [97]. Such work must be compared to experimental results from both the deuteron and $^3$He to establish the reliability of neutron extraction.

Measurements at forward angle can be difficult due to increasing backgrounds and the growing importance of radiative corrections. We note that the analysis of the lowest $Q^2$ data of experiment E97-110 will be complicated by the miswiring of the septum magnet used to detect the forward electrons for part of the Hall A run. This problem will increase the systematic uncertainties on the lowest $Q^2$ points [29]. Finally, simulations show that the lowest $Q^2$ reachable with the combination of CLAS and the new Cerenkov is 0.01 GeV$^2$ [26], a factor of two times lower than the lowest $Q^2$ point covered by E97-110.

It is not the goal to the this proposal to improve on the measurement done in Hall A, aside from providing the necessary data to have confidence in the neutron extraction method. It is difficult to compete with results from a polarized $^3$He target given the present performance of polarized $ND_3$ targets. However, we can reach a comparable precision below $Q^2 \approx 0.1$ GeV$^2$ where the neutron extraction method starts to be unreliable and where a cross check is most valuable. Also, due to the low angle coverage of the new CLAS Cerenkov detector, and to the fact that the $^3$He experiment encountered technical difficulties, an experiment in Hall B would provide better accuracy for the very low $Q^2$ points as illustrated in fig 7.

## 2.2 Testing $\chi$PT

The JLAB results on GDH at intermediate Q$^2$ [30, 23, 24, 89] triggered discussions showing a large interest for pushing measurements to smaller Q$^2$. It is clear from the neutron results on spin polarizabilities [30], especially for the longitudinal-transverse polarizability $\delta_{LT}$, that more theoretical work is needed to understand the data and the transition from partonic to hadronic degrees of freedom of the strong interaction. Similarly, preliminary results from the 1.6 GeV EG1 results on the proton and the deuteron show consistency with $\chi$PT calculations as high as $Q^2$ = 0.1 but only within the large statistical and systematic uncertainties of the data (see Fig. 1). $\chi$PT calculations are the only rigorous computations available presently for I(Q$^2$) at low momentum transfer [31, 32]. However, there are several theoretical issues regarding the accuracy and domain of application of $\chi$PT. For example:

1. The prediction for the slope of I(Q$^2$) at the photon point changes sign when going from leading order to next to leading order, so it is not obvious that the first few terms of the chiral expansion are sufficient for establishing a reliably convergent $\chi$PT prediction.
2. The importance and method of inclusion of the resonances in $\chi$PT calculations is still uncertain.
3. The Q$^2$ range of applicability of $\chi$PT needs to be tested.

Providing data at the lowest possible $Q^2$ is crucial to constrain the $\chi$PT calculations and to address these issues.

A check on $\chi$PT on the neutron will necessarily be less accurate than its proton counterpart. However, a satisfactory understanding of $\chi$PT has to include both nucleons even if one of them is harder to access.

### 2.2.1 Generalized Spin Polarizabilities

The spin polarizabilities are fundamental observables that characterize nucleon structure and present one of the best tests of $\chi$PT calculations at low $Q^2$. Like the GDH sum, they are related to integrals of the nucleon excitation spectrum and rely on the same basic theoretical assumptions. At the real photon point, the electromagnetic polarizabilities reflect the nucleon's response to an external electromagnetic field. The generalized polarizibilities represent an extension of these quantities to virtual photon compton scattering at finite $Q^2$. The polarizabilities are expected to converge faster than the first moments and thus reduce the dependence of measurements on extrapolations to the unmeasured regions at large $\nu$.

## 2.3 Extrapolation to the Real Photon Point

Measuring the GDH sum rule by extrapolation from nearly real photon data would provide a completely independent cross-check of the techniques presented in section 1.1.1. In particular, measuring the GDH sum at the photon point demands detection of hadrons while at finite $Q^2$, a simpler inclusive measurement is sufficient. We present three possible scenarios that may be encountered in an attempt to extrapolate to the real photon point:

1. The data is found to exhibit linear behaviour at low $Q^2$. In this case it will be straightforward to extrapolate to $Q^2 = 0$.

2. We find a more complicated dependence with $Q^2$ that agrees with $\chi$PT calculations. We may then utilize the $\chi$PT calculations to guide the extrapolation. (We note, however, that the available calculations all predict linear behavior at present.)

3. The data exhibits a complicated $Q^2$ dependence *and* disagrees with $\chi$PT. This would make the extrapolation difficult, but is perhaps the most interesting and exciting possibility as it would require a serious re-examination of the fundamental precepts of $\chi$PT.

We discuss the systematic uncertainty of such an extrapolation in section 4.5.

## 2.4 The Bjorken Sum at Low $Q^2$

In combination with the E03-006 proton data, we can form the difference $I^p - I^n$ which is predicted at the photon point by the GDH sum rules on the proton and the neutron. This is the best quantity to extrapolate to the photon point since its evolution is smoother than the individual nucleon integrals due to the partial cancellation of the resonance contribution [27]. For the same reason, the Bjorken sum is also calculable

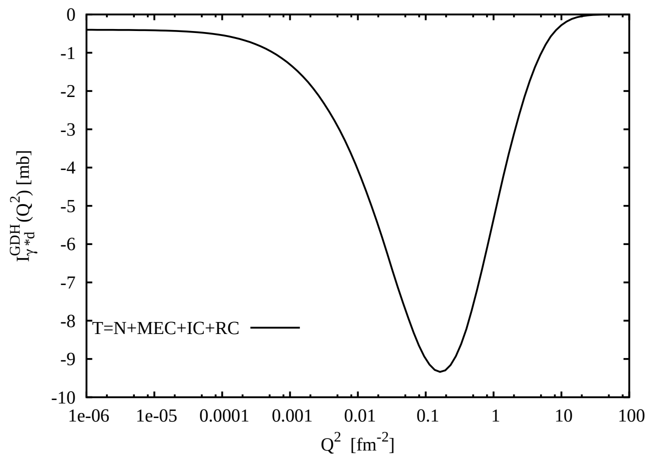


Figure 2: Generalized GDH integral as a function of $Q^2$ for deuteron electrodisintegration $d(e,e')np$ from Ref. [2].

in $\chi$PT with a range of applicability that is expected to be larger than for the GDH integral. In fact, the upper $Q^2$ limit of $\chi$PT calculations for the Bjorken sum is expected to approach the range of applicability of the Higher Twist Expansion. At large $Q^2$, the Bjorken sum is the only moment for which the absolute value is predicted, in contrast for example to the Ellis-Jaffe sums. Furthermore, its $Q^2$ behavior at leading twist is simpler and does not involve gluon distributions because only non-singlet coefficients enter in the operator product expansion. Finally, since the Bjorken sum is both a moment and a flavor non-singlet quantity, it is particularly suitable for Lattice QCD calculations. Hence, it appears that the Bjorken sum is the perfect quantity to provide benchmark measurements for the three theoretical frameworks that are used to understand the transition from hadronic to partonic degrees of freedom. It is therefore a most important object to measure accurately on the entire $Q^2$ range.

An experiment in Hall B under the same circumstances as E03-006 would minimize the point to point systematic errors. In fact, the $Q^2$-evolution is often more important than the absolute value of the sum since calculations often deal only with the $Q^2$-behavior. Examples are analyses within the Operator Product Expansion framework (extraction of higher twists [37]) or comparison to $\chi$PT. Experiments done on both nucleons under the same experimental conditions would provide the best condition for an accurate comparison to theories.

## 2.5 The Deuteron Extended GDH Sum at low $Q^2$

The deuteron extended GDH sum rule is an intriguing quantity in its own right in addition to its utility to provide access to the neutron. As in the case of real photon scattering, the disintegration channel is expected [8, 2] to play a crucial role, providing a large negative contribution that very nearly cancels the sum of all contributions

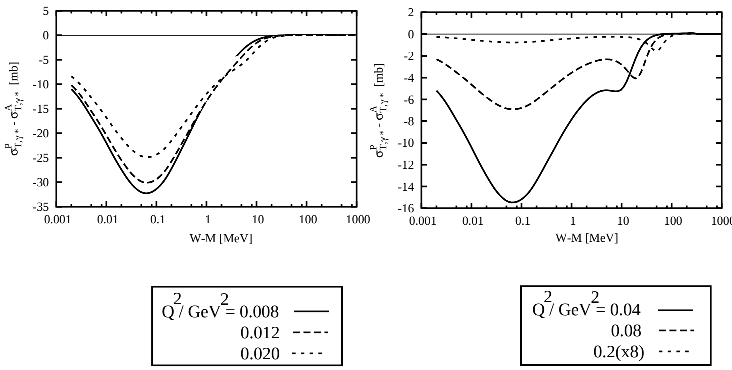


Figure 3: Transverse spin asymmetry of $d(e,e')np$ for various values of $Q^2$. The small contribution above 10 MeV at large $Q^2$ is the quasi-elastic reaction, which dies off at lower momentum transfer. Calculations based on Argonne $V_{18}$ potential including interaction and relativistic effects. Plot from Ref. [2].

from meson production. Arenhovel *et al.* predict that the electrodisintegration channel contribution is largest for $Q^2 \approx 0.2$ fm$^{-2}$ which is near the low kinematic range of this proposal (see fig 2). The electro-disintegration channel of $^3$He [38] and the deuteron [39] have been investigated previously at JLab and measuring the deuteron GDH integral as a function of $Q^2$ will provide a significant test of present theoretical understanding of the properties of few-body nuclei [2]. Furthermore, $\chi$PT calculations are becoming available for nuclei [40] without the issue of nuclear corrections. The logical choice to check these new calculations is the deuteron, since it is the lightest nucleus. We note that at the proposed kinematics, the quasielastic reaction will be insignificant compared to electrodisintigration, as displayed in figure 3, so separation of these two channels will not present any difficulty. A complete deuteron measurement will be challenging experimentally because of the difficulty of separating the elastic scattering contribution on the deuteron from the inelastic states, beginning with the breakup channel at 2.2 MeV. However, we note that the previous EG1 experiments were not hindered by the coherent elastic contribution. Because of this, we believe we can certainly make a clean deuteron measurement at our largest few proposed $Q^2$ points, a region that is still useful for a $\chi$PT test, and we will make all our data available and work with theorists to determine whether we can place any constraints on $\chi$PT calculations on the deuteron.

Since it is unclear at the moment at exactly which $Q^2$ the separation between elastic and electro-disintegration will become problematic, in the rest of this document, our estimate on deuteron quantities will include only the incoherent part of $I(Q^2)$, ie the contribution beginning from the pion-production threshold. We note that all previous EG1 experiments analyzed only this part of the GDH integral.

## 2.6 Experimental Considerations

Measurements of inelastic reactions at low $Q^2$ are in general harder to carry out. This is due to large radiative corrections and increasing backgrounds. A cross check of E97-110 and this proposed experiment, using completely different targets and detection systems, is not a motivation in itself. However, it would provide additional confidence in the measurements. It is also worthwhile to note that the CLAS detector will redundantly measure several kinematic bins, but with different angles and beam energy (see overlap in Fig. 4). There will therefore be different backgrounds and radiative corrections, and will provide an important self cross-check of our measurement.

| Observable | D target: Experiment | D target: $Q^2$ in $\mathrm{GeV}^2$ | $^3$He target: Experiment | $^3$He target: $Q^2$ in $\mathrm{GeV}^2$ |
|---|---|---|---|---|
| $g_1^n$ & $\Gamma_1^n$ at large $Q^2$ large $Q^2$ | SLAC E143 (1995)[76] | $< Q^2 >= 3$ | SLAC E142 (1996)[85] | $< Q^2 >= 2$ |
| | SMC (1998) [77] | $< Q^2 >= 10$ | SLAC E154 (1997) [86] | $< Q^2 >= 5$ |
| | SLAC E155 (2000)[80] | $< Q^2 >= 5$ | HERMES (1998) [79] | $1.5 < Q^2 < 15$ |
| | HERMES (2003) [78] | $1.5 < Q^2 < 15$ | JLab E99-117 (2004) [88] | $2.7 < Q^2 < 4.8$ |
| | JLab EG1 (2003) [81] | $0.05 < Q^2 < 5$ | JLab E01-012 [90] | $1 < Q^2 < 4.0$ |
| | JLab SANE [82] | $2.5 < Q^2 < 8.5$* | | |
| $g_2^n$ & $\Gamma_2^n$ at large $Q^2$ | SLAC E143 (1995)[76] | $< Q^2 >= 3$ | SLAC E142. (1996) [85] | $< Q^2 >= 2$ |
| | SLAC E155(2000) [80] | $< Q^2 >= 5$ | SLAC E154 (1997) [87] | $< Q^2 >= 5$ |
| | JLab SANE [82] | $2.5 < Q^2 < 8.5$* | JLab E99-117 (2004) [88] | $2.7 < Q^2 < 4.8$ |
| $\Gamma_1^n$ at low $Q^2$ | SLAC E143 (1995)[76] | $0.5 < Q^2 < 1.2$ | HERMES (1998)[79] | $1.5 < Q^2 < 15$ |
| | HERMES (2003) [78] | $1.5 < Q^2 < 15$ | JLab E94-010 (2002) [89] | $0.1 < Q^2 < 0.9$ |
| | JLab EG1 [83] | $0.05 < Q^2 < 5$ | JLab E97-103 (2005) [91] | $0.57 < Q^2 < 1.34$ |
| | JLab RSS [84] | $< Q^2 >= 1.3$ | | |
| $\Gamma_2^n$ at low $Q^2$ | JLab RSS [84] | $< Q^2 >= 1.3$ | JLab E94-010 (2002) [89] | $0.1 < Q^2 < 0.9$ |
| | | | JLab E97-103 (2005) [91] | $0.57 < Q^2 < 1.34$ |
| $\Gamma_1^n$, nearly real photons | / | | JLab E97-110 [92] | $0.02 < Q^2 < 0.3$ |
| $\Gamma_2^n$, nearly real photons | / | | JLab E97-110 [92] | $0.02 < Q^2 < 0.3$ |
| $G_M^n$ | DESY (1973)[61] | $0.7 < Q^2 < 3$ | Bates (1994)[59] | $Q^2 = 0.19$ |
| | SLAC NE11 (1992)[58] | $1.8 < Q^2 < 8.9$ | JLAB E95001 (2000)[60] | $Q^2 = 0.1 - 0.6$ |
| | Bates (1993)[62] | $0.11 < Q^2 < 0.26$ | | |
| | NIKHEF (1994)[64] | $Q^2 = 0.58$ | | |
| | ELSA (1995)[66] | $0.13 < Q^2 < 0.61$ | | |
| | MAMI (1998)[65] | $0.2 < Q^2 < 0.8$ | | |
| | MAMI (2002)[67] | $0.07 < Q^2 < 0.9$ | | |
| | JLab E94017 (2005)[51] | $\sim 0.5 < Q^2 < 5$ | | |
| $G_E^n$ | DESY (1971) [68] | $0.19 < Q^2 < 0.54$ | MAMI (1994)[70] | $< Q^2 >= 0.31$ |
| | DESY(1973)[61] | $0.7 < Q^2 < 3$ | MAMI (2003) [52] | $< Q^2 >= 0.67$ |
| | SACLAY (1990)[69] | $0.04 < Q^2 < 0.70$ | JLab E02-013 [72] | $1.3 < Q^2 < 3.4$* |
| | Bates (1994)[63] | $Q^2 = 0.26$ | | |
| | MAMI (1999)[56] | $Q^2 = 0.15$ | | |
| | NIKHEF (1999)[54] | $Q^2 = 0.21$ | | |
| | MAMI (1999)[55] | $Q^2 = 0.34$ | | |
| | Quadrupole F.F. data (2001)[53] | $0. < Q^2 < 1.63$ | | |
| | JLab E93026 (2001)[57] | $Q^2 = 0.5$ | | |
| | JLab E93-038 (2003)[73] | $Q^2 = 1.45$ | | |
| | MAMI (2005) [75] | $0.3 < Q^2 < 0.8$ | | |
| | JLab E04-110 [74] | $Q^2 = 4.3$* | | |

Table 1: This table lists neutron structure measurements both existing and planned. While systematically done at large $Q^2$ and for the elastic reaction, the $^3$He/Deuteron cross-check is missing at low $Q^2$ for the spin structure functions where it is most important. An asterix indicates the expected $Q^2$ coverage for on-going or future experiments.

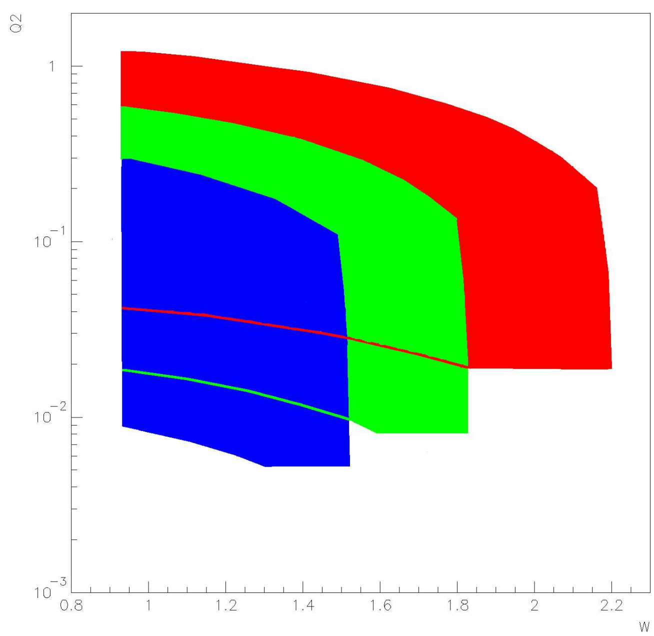


Figure 4: Proposed kinematic coverage for three incident energies: 3.2, 1.6 and 1.1 GeV. Not shown is the short 0.8 GeV run for radiative correction studies.

# 3 Proposed Measurement

## 3.1 Kinematics

We propose to cover the kinematic range[‡] displayed in figure 4, which requires three incident beam energies: 1.1, 1.6 and 2.2 GeV. This will allow us to evaluate the $Q^2$-evolution of the GDH integral from 0.01 to 0.2 GeV$^2$. A short run with a 0.8 GeV beam, not shown in the figure, will help reduce the systematic uncertainties arising from the radiative corrections. In figure 4, any region where the elastic tail is expected to be prohibitively big has been excluded, leading to the cutoffs at low $Q^2$.

## 3.2 Experimental Setup

In order to perform an absolute cross section measurement, we plan to use a modified setup which includes the new Čerenkov counter that is being commissioned for E03-006. This detector is specifically designed for the outbending field configuration which is necessary to reach the desired low $Q^2$. This new detector will have a very high electron detection efficiency (of the order 99.9%) to allow the measurement of the absolute cross section with minimal corrections and a high pion rejection ratio (of the order $10^{-3}$). The other components of CLAS will be in standard configuration.

[‡] The proposed kinematics are similar to experiment E03-006 except for the 3.2 GeV incident energy.

We will use the JLab/UVA $ND_3$ polarized target [41] used in previous CLAS spin-dependent measurements. This target exploits the Dynamical Nuclear Polarization (DNP) technique to polarize the material which is maintained in a liquid helium bath at 1 K and in a 5 Tesla longitudinal field. This system operated successfully in previous CLAS runs, providing typical deuteron polarizations of 35%. The deuteron polarization will be monitored online by an NMR system and then extracted offline by the analysis of quasi-elastic scattering events which are recorded simultaneously with the inelastic events thanks to the large CLAS acceptance. This method provides a more precise measurement of the product of beam and target polarization than does the individual measurements of the electron polarization using the Moller polarimeter and the target polarization using the NMR. The polarized target will be retracted by 1 m upstream to increase the acceptance at low $Q^2$, by reducing the minimal angle for the scattered electron, allowing to reach $Q^2 = 0.01$ GeV$^2$. The target will contain two $^{12}$C inserts of differing thickness, and an empty cell in addition to the $ND_3$ for background measurements. Each of these cells can be moved into the beam via remote control. In addition we will use a solid nitrogen target to check the nitrogen contribution. There will be two $ND_3$ cups 1 cm, and 0.5 cm in length respectively. Both will be 1.5 cm in diameter.

We will exploit the highly polarized JLab electron beam. Previous experiments have shown that a typical polarization of 80% can be expected. Beam currents in the range of 1-4 nA will be used. In these conditions, no significant heating of the target material takes place. The beam will be rastered over the target surface to minimize radiation effects, using the existing Hall B raster. Due to the low beam current and the rastering, radiation damage to the target material will be limited, and annealing will be required only once per week. The beam polarization will be measured by the Hall B Moller polarimeter, while as mentioned above the final value of the product of beam and target polarization will be extracted from the quasi-elastic data.

We note that the experimental setup is the same as for experiment E03-006, apart from the target cell used. E03-006 is scheduled to run in 2006, and requires installation of the polarized proton target and a new Cerenkov detector, currently under construction at INFN. If the experiment described in the present proposal ran just after or during E03-006, one would take advantage of this to minimize both the beam down time and the use of manpower in Hall B.

We will trigger CLAS by requiring a coincidence between the electromagnetic calorimeter and the new INFN Cerenkov counter, which will be installed in only one sector. We will not accept electron triggers from other sectors of CLAS. In fact, in order to maximize our useful data rate for scattered electrons, we will turn off the other five sectors of CLAS.

### 3.3 Extraction of $g_1$

The use of absolute cross section differences is a robust way of extracting $g_1$ because the unwanted unpolarized contribution cancels out. This extraction technique meets its full interest with the $ND_3$ target where the amount of unwanted (non-deuteron) target material is necessarily large.

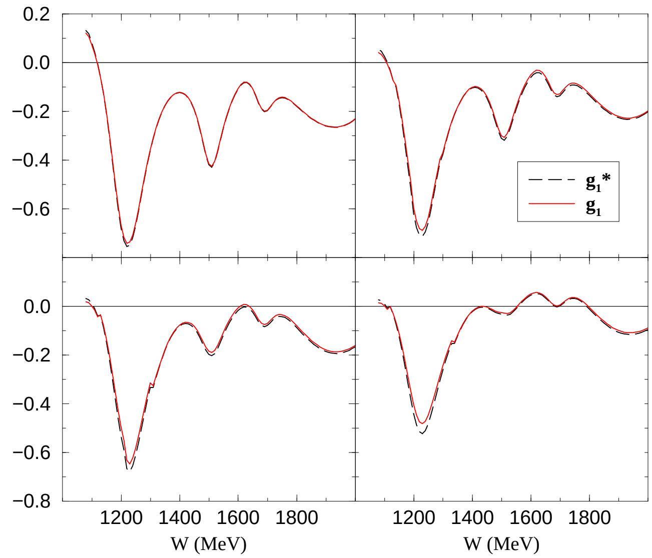


Figure 5: The effect of neglecting $\Delta\sigma_\perp$ on $g_1$. In the plots, $g_1^*$ represents eq. 4 with $\Delta\sigma_\perp$ set to zero. Top Left: $Q^2 = 0.01$ Top Right: $Q^2 = 0.05$ Bottom Left : $Q^2 = 0.1$ Bottom Right : $Q^2 = 0.2$

The spin structure function $g_1$ is related to the spin-dependent cross sections via:

$$g_1 = \frac{MQ^2}{4\alpha^2}\frac{y}{(1-y)(2-y)}\left(\Delta\sigma_\parallel + \tan\frac{\theta}{2}\Delta\sigma_\perp\right) \tag{4}$$

Here $\Delta\sigma_\parallel = \sigma^{\uparrow\Uparrow} - \sigma^{\downarrow\Uparrow}$, and $\Delta\sigma_\perp = \sigma^{\uparrow\Rightarrow} - \sigma^{\downarrow\Rightarrow}$ with the first superscript indicating the electron spin, while the second refers to the target spin orientation. The Hall B polarized target can be polarized only in the longitudinal direction at present, so there will be some error introduced by neglecting the perpendicular term in eq. 4. We have estimated this effect by evaluating the contribution of $\Delta\sigma_\perp$ to $g_1$ using a fit to world data [43]. Figure 5 reveals that at the proposed kinematics, the effect of neglecting the $\Delta\sigma_\perp$ contribution is indeed quite small. Neglecting $\Delta\sigma_\perp$ entirely results in a maximum 5% difference in $\Gamma_1$ at our highest $Q^2$, and falls to less than 1% at $Q^2 = 0.01$ GeV$^2$. (See table 2). These results are in general agreement with the EG1B systematic analysis [44]. The systematic effect will be smaller than this of course and will depend on the accuracy of the model used to estimate the perpendicualar contribution. Following the EG1B analysis, we assume conservatively 50% uncertainty on the model input, which can be reduced with more careful studies in the future.

## 3.4 Rates and Beam Time Estimate

Ostensibly, the rates and beam time request of this proposal will be similar to approved experiment E03-006. We must however adjust for the variation of rates due to the dif-

| $Q^2$ (GeV$^2$) | $\Gamma_1^*$ | $\Gamma_1$ | Difference |
|---|---|---|---|
| 0.01 | -0.0070620 | -0.0070220 | 0.6% |
| 0.05 | -0.0298287 | -0.0292262 | 2.1% |
| 0.10 | -0.0456892 | -0.0442065 | 3.4% |
| 0.20 | -0.0489075 | -0.0464575 | 5.3% |

Table 2: Uncertainty in $g_1$ due to the lack of transverse data. $\Gamma_1^*$ represents the first moment of eq. 4 evaluated [43] assuming $\Delta\sigma_\perp = 0$.

fering targets and attainable target polarizations, and also for improvements in various JLab instrumentations.

The expected counting rates [26] for inelastic scattering from proton were estimated assuming: a $W$ bin of 20 MeV, a $Q^2$ bin of 0.01 GeV$^2$, a polar angular interval $\Delta\phi$ of 18° for one module of the Čerenkov detector, a beam current ranging rom 1 to 4 nA depending on the energy, and beam energies of 1.1, 1.6, and 2.4 GeV. We assumed a minimum electron detection angle of 5 degrees. A minimum energy for the outgoing electron of 300 MeV was also assumed in integration to obtain the GDH sum. The unpolarized inclusive electron scattering cross section was calculated based on a parameterization of the two structure functions $F_1$ and $F_2$ [43].

We assume a target polarization of $40\%$, a beam polarization of $80\%$, and an improved DAQ rate of 6 khz. Taking into account the $ND_3$/$NH_3$ target nucleon ratio we arrive at the beam time estimate displayed in Table 3 . We have excluded the E03-006 3.2 GeV incident energy and added a very short run at 0.8 GeV to ensure we completely control our radiative corrections. This energy setting will be dedicated to an unpolarized measurement of the elastic radiative tail and as such requires a small amount of beam time. Given this allotment we can gather 65% of the data of the proton measurement, which translates to a 25% larger statistical uncertainty.

The expected precision can be seen in figs 6 and 7. In fig. 7, we assumed 20% systematic uncertainty on the procedure for neutron extraction from both $^3$He and D. However, as discussed in appendix A, no calculations are available for now. A comparison of neutron results extracted from D to those extracted from $^3$He would give an estimate on the size of the nuclear corrections and hence would constrain to the same level the accuracy of the neutron extraction procedure. Adding in quadrature the systematics errors on the n from D and n from $^3$He (ignoring the uncertainty due to the model extraction) yield typically about 20% (or 30% if the uncertainties are added linearly). This is the level to which the procedure for neutron extraction will be checked.

Let us note that this number is relevant only to the particular problem of extracting neutron. Nuclear models themselves will be further constrained by directly comparing our doubly polarized data to model predictions.

#### 3.4.1 Overhead

We present two possible scenarios:

1. If the current proposal runs in conjunction with E03-006, the overhead is mini-

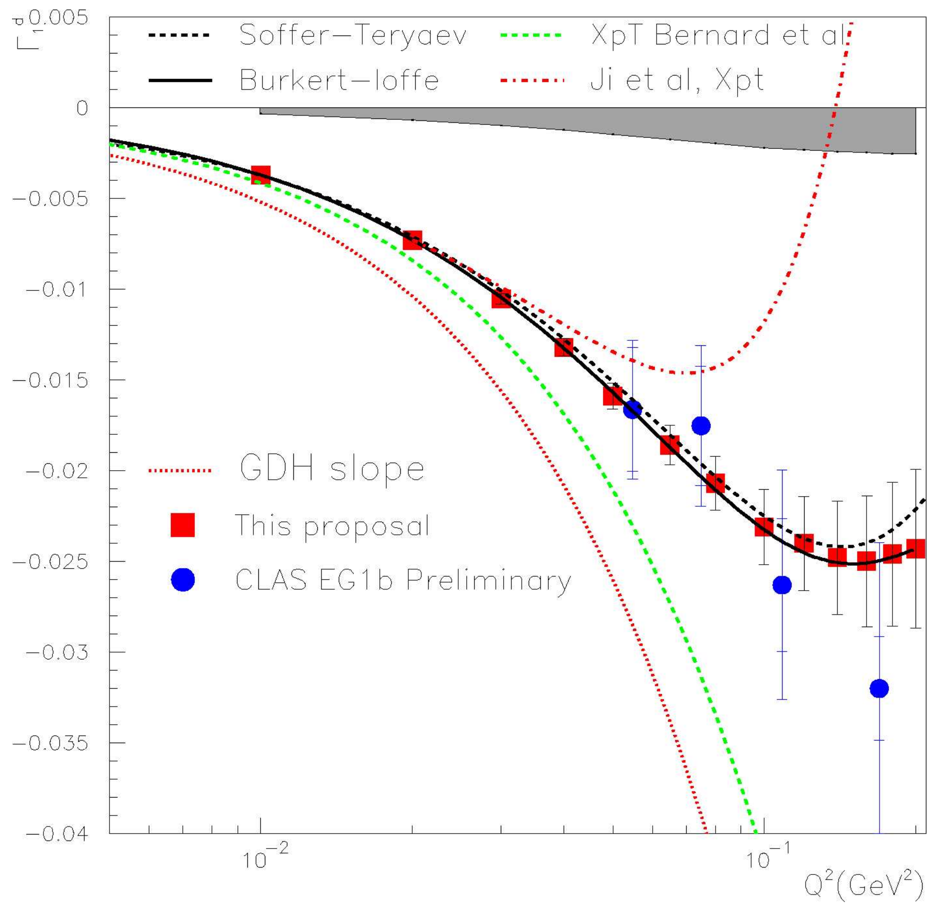


Figure 6: Expected precision of deuteron $\Gamma_1$. The band represents the systematic uncertainty, while the error bars on the points are statistical only. The curves from Bernard *et al.* [31] and Ji *et al.* [17] are $\chi$PT calculations. The curve from Burkert-Ioffe [47] and Soffer-Teryaev [33] are phenomenological models. The preliminary EG1B data [83] are shown for comparison.

| Energy (GeV) | days | current (nA) |
|---|---|---|
| 0.8 | 0.3 | 1 |
| 1.1 | 9 | 1 |
| 1.6 | 10 | 2 |
| 2.4 | 10 | 4 |
| Total | 29 | |

Table 3: Beam Request Summary.

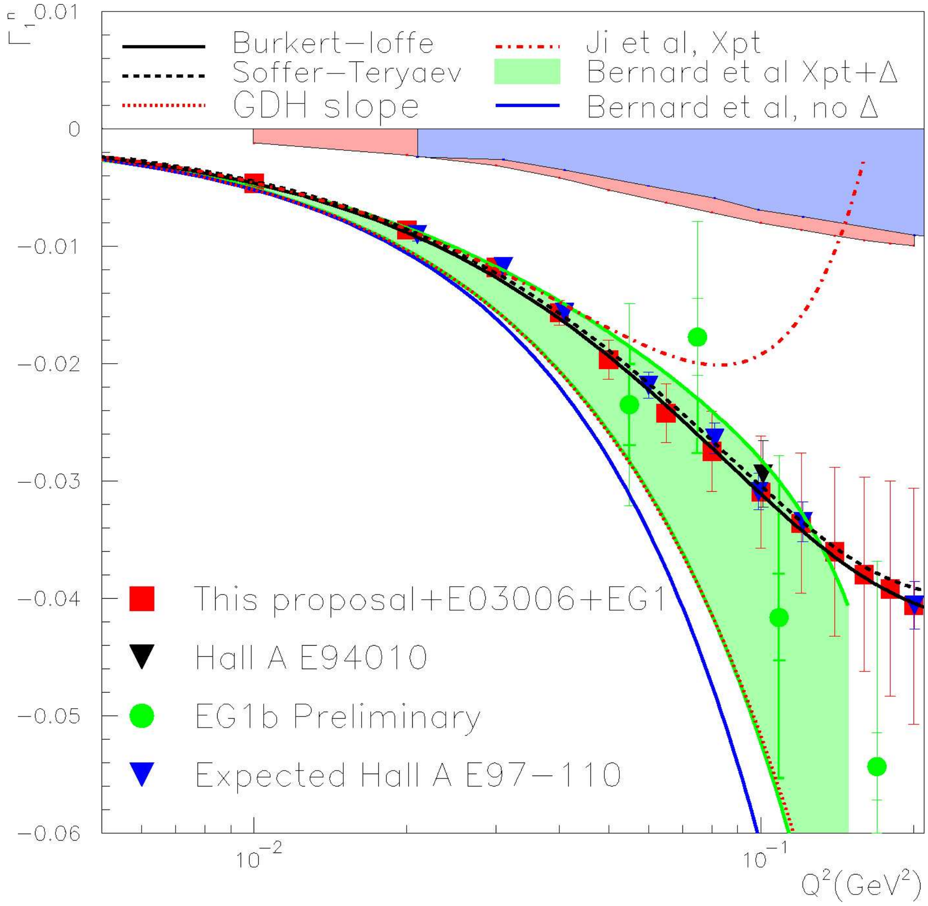


Figure 7: Expected precision of neutron $\Gamma_1$. The error bar contains both statistical and systematic uncertainty. We assume 20% uncertainty from the neutron extraction from both $^3$He and the deuteron. The projected uncertainties for the present proposal include the error on the proton measurement. The relevant domain for comparing neutron extracting from $^3$He and D is below $Q^2 \sim 0.1$, where the known method to extract the neutron becomes less reliable. The points at higher $Q^2$ are ancillary results coming from the higher beam energy runs necessary to expand the $W$ coverage of the lower $Q^2$ points. See fi g. 6 for a description of theoretical curves.

mal, namely the replacement of the NH3 target stick with the ND3 target stick for each kinematic. This will require approximately 8 hours for each target swap.

2. If the current proposal runs independently, then there are several new overhead requirements: We estimate 2 hours required for a pass change, and one 8 hour shift required for linac change. Given our kinematic request this would require 20 additional hours of beamtime.

Previous polarized target runs have demonstrated that the necessity to anneal the target has minimal impact on beamtime, as this procedure can be scheduled during weekly beam studies. Furthermore, the annealing procedure will be required less frequently due to the low current used in Hall B.

This brings the total requested beamtime including overhead to 29.8 days.

# 4 Systematic Uncertainties

## 4.1 Polarized cross section

One limiting factor in measuring quantities with the polarized target is the precise knowledge of target thickness. Measurements will be made after the experimental run to measure it at the % level (for example by melting the ammonia beads and measuring the volume of ammonia). The total luminosity will be also monitored by continuous measurement of the quasi-elastic cross section. Such measurement will be used as well to extract the product of the beam and target polarizations.

All in all, we expect a 5% systematic accuracy [42] on the unpolarized cross section measurement before radiative corrections, and 5% on the asymmetry. These two quantities are used to form the difference of polarized cross sections.

## 4.2 Radiative corrections

Radiative corrections are needed to extract the Born cross section from the measured one. This procedure is well established for both unpolarized [45] and polarized [46] scattering.

At the low momentum transfer of this proposal, elastic radiative tails can limit a meaningful extraction of $g_1$ from background contamination. We are presently studying the magnitude of the radiative tail effects, and detailed calculations will be available shortly. We expect to control the radiative tails systematics uncertainty from external radiative corrections by running with different target thickness (0.5 and 1 cm). Together with this systematic check, a short run at 0.8 GeV beam energy will allow to minimize the uncertainty on the total (internal and external) radiative tails. Finally, data from regions where the elastic tail is large (cross section a few time larger than the inelastic signal) will not be used in the analysis (see Fig. 4). One of the main effect of the radiative corrections is to redistribute the events along the target excitation spectrum. Since we are interested by the integral over the excitation spectrum, the overall effect of the radiative corrections is somewhat reduced. All in all, we assume a systematic uncertainty of 5% or better.

The overlap of kinematic coverage from different incident energies (with different radiative corrections) will help ensure that we understand the systematic to this level.

### 4.3 Large $W$ extrapolation.

An extrapolation to large $\nu$ is needed to account for the unmeasured high energy contribution. The uncertainty on the sum due to this missing part is not larger than 2%. This has been estimated in the following way: we evaluate the total sum $\Gamma_1^d$ using the model of Burkert and Ioffe [47] which agrees well the JLab data taken at intermediate and large $Q^2$ (see for example [48]). The size of the unmeasured part of $\Gamma_1^d$ is estimated using the Bianchi-Thomas parameterization [49] based on a Regge form constrained by the polarized world data. A 50% uncertainty on the magnitude of the missing part was taken as the uncertainty on the total sum. In the above calculation, the deuteron was formed using the proton and neutron predictions according to the formula:

$$I^D = \frac{I^p + I^n}{2(1 - 1.5\omega_D)} \tag{5}$$

with $\omega_D \simeq 0.05$.

### 4.4 Other systematics effects

A large nitrogen background is present when ammonia polarized targets are used. This background is mostly unpolarized and cancels out in the difference of polarized cross sections. The slight remaining polarization of the $^{15}$N will need to be corrected. We expect 1 to 2% uncertainty on the cross section due to this correction.

Another systematics effect in the measurement of polarized cross section could come from beam charge asymmetry. We do not expect significant effects since the JLab beam source is equipped with parity violation quality monitoring and feedback devices.

### 4.5 Extrapolation to $Q^2 = 0$

The expected errors on the GDH sum rule at the photon point can be estimated by extrapolating the measurement at our lowest $Q^2$ point using five[§] available theory predictions normalized the data. The dispersion of the results gives some indication of the uncertainty due to extrapolation that we may expect. The lowest $Q^2$ point is well into the domain where all available calculations predict linear behavior. Thus, the uncertainty on the extrapolation is dominated by our experimental systematic.

Following this estimate, we expect a 9% uncertainty on the incoherent deuteron GDH sum (i.e. the contribution above the pion production threshold). The statistical uncertainty is negligible (0.9%). This accuracy is similar to the precision of the GDH verification made at MAMI and ELSA on the proton [9, 10].

[§]The slope predicted by the GDH sum rule, $\chi$PT calculations from Ji *et al.* [17], and Bernard *et al.* [31], and the phenomenological models of Soffer and Teryaev [33], and Burkert and Ioffe [47].

| $Q^2$ (GeV$^2$) | $\delta_{DIS}$ | $\delta_{trans}$ | $\delta\sigma_{born}$ | $\delta^{tot}_{syst}$ | $\delta_{stat}$ |
|---|---|---|---|---|---|
| 0.01 | 1.6 | 0.3 | 8.9 | 9.0 | 1 |
| 0.02 | 2.2 | 0.7 | 8.9 | 9.2 | 2 |
| 0.05 | 1.5 | 1.1 | 8.9 | 9.1 | 5 |
| 0.10 | 1.1 | 1.7 | 8.9 | 9.1 | 9 |
| 0.15 | 0.2 | 2.2 | 8.9 | 9.2 | 16 |
| 0.20 | 1.1 | 2.7 | 8.9 | 9.4 | 22 |

Table 4: Systematic uncertainty (in percent) on $\Gamma_1^d$. For reference we list the expected statistical precision in the final column.

The uncertainty on the neutron GDH sum would be 25%, assuming a 20% uncertainty due to the neutron extraction from the deuteron. This uncertainty should decrease with theoretical progress in the nuclear corrections. An uncertainty of 10% on neutron extraction procedure would reduce the uncertainty on the neutron GDH to 18%.

# 5 Total Uncertainty

Table 4 gives the uncertainties on $\Gamma_1^d$ for different $Q^2$ points, which we describe here in detail:

- $\delta_{DIS}$ : the uncertainty on $\Gamma_1^d$ due to the unmeasured contribution to the integral from $W = W_{max}$ to $W = \infty$, assuming a 50% accuracy of the model. $W_{max} =$ 2.2 GeV for all points except the first, for which the upper limit is 1.8 GeV.

- $\delta_{trans}$ : the uncertainty due to the absence of transverse target spin data. This error is discussed in detail in section 3.3.

- $\delta\sigma_{born}$ : the uncertainty on the absolute polarized cross section difference after radiative corrections. This include the uncertainties on absolute unpolarized cross section, asymmetries, polarized $^{15}$N background and radiative corrections.

- $\delta^{tot}_{syst}$ : the total systematic uncertainty, added in quadrature.

- $\delta_{stat}$ : the statistical uncertainty.

# 6 Summary

In summary, we propose to measure the extended GDH integral on the neutron and deuteron in the range 0.01<Q$^2$<0.2 GeV$^2$. The main goals of this measurement are:

1. To measure the neutron GDH integral extracted from the deuteron, which is a necessary complement to the data already taken on $^3$He (Hall A experiment E97-110 [1]). The nuclear corrections involved in the extraction of neutron from a polarized nuclear target are increasingly complex and sizable at low $Q^2$ and must be verified for different nuclear mediums;

2. To provide a check of $\chi$PT calculations for the neutron;

3. To measure the Bjorken sum at very low $Q^2$ when combined with proton data from Hall B experiment E03-006 [26]. The similar experimental setup of the two experiments will minimize any relative systematic uncertainty.

Additionally, such a measurement would provide:

1. A check of the (real photon) GDH sum rule on the neutron and deuteron via extrapolation to $Q^2 = 0$;

2. A benchmark measurement for Chiral Perturbation Theory calculations of the deuteron at low $Q^2$.

3. Insight into the role the disintegration channel plays in the satisfaction of the deuteron GDH sum rule.

The proposed measurement is very similar to the approved proton GDH experiment, E03-006. With 30 days beam time we can reach a statistical precision at the level of the proton measurement with a similar systematic uncertainty.

# A Extraction of Neutron Quantities from $^3$He and D.

Neutron information is essential to our understanding of the strong interaction and nucleon structure. Many groups have worked out extraction procedures [93]-[112], although this list of references is not exhaustive. We will focus here mainly on the work of Ciofi Degli Atti and collaborators.

In the description below, the limitations of the extraction procedures will be apparent, thus demonstrating the need for experimental results from both D and $^3$He. Tests against both D and $^3$He experimental results will be needed to establish the reliability of the more sophisticated procedures that are necessary to extract the neutron.

## A.1 $^3$He

In Experiment E97-110, neutron information has to be extracted from $^3$He data. The $^3$He nucleus is not in a pure S state. The admixture of S$'$ and D states can reach about 10%. This makes the protons of the $^3$He nucleus come into play. In DIS, this can be formalized using the concept of non-zero proton effective polarization $P_p \neq 0$. For the same reason part of the neutron spin is pointing in the opposite direction than the $^3$He spin (neutron effective polarization $P_n < 1$). Other nuclear corrections accounted for in this extraction procedure come from the Fermi motion and the binding. The correction method for DIS data was first worked out for $^3$He by Friar et al. [93] and then by C. Ciofi Degli Atti et al. [94]. The method was then applied to the GDH sum rule by C. Ciofi Degli Atti and S. Scopetta [95].

The proton and neutron effective polarizations within the $^3$He nucleus are computed either using three-body Fadeev calculations or by integrating elements of the matrix representing the spin dependent spectral function (both methods agree). Without any nuclear effects other than the admixture of the S$'$ and D states, the different spin structure functions would obey the equation:

$$g^{^3He} = 2p_p g^p + p_n g^n \tag{6}$$

with $p_p = -0.028 \pm 0.004$ and $p_n = 0.86 \pm 0.02$ [94].

Assuming that the spin structure functions have the same form for a bound nucleon and a free nucleon, then the Fermi motion and binding effect can be taken into account by integrating the structure functions over a shifted energy transfer, *i.e.*, these effects are accounted for by convoluting $g_1$ and $g_2$ with a quantity related to the $^3$He spectral function [94] calculated in the plane wave impulse approximation (PWIA). This method holds in principle for the quasi-elastic, resonances and DIS domains. Ciofi Degli Atti *et al.* demonstrate that in the DIS region Eq. 6 is already a good approximation and the refinement by the convolution method modifies the result by at most 4% (for $x < 0.8$) [94]. However in the resonance region Eq. 6 is not sufficient for a reliable extraction of the neutron data [95] due to Fermi motion and binding.

Since the generalized GDH integral is an integration over the spin structure function $g_1$, the method used to extract the spin structure functions on the neutron can also be applied to the generalized GDH integral. A comparison of the extraction of the neutron GDH integral using, on the one hand, only the effective polarizations method (cf Eq. 6) and, on the other hand the PWIA method, shows that in both cases the GDH integral is similar. Hence, for integrated quantities, in a domain where PWIA is justified, the neutron can be extracted either by simply accounting for effective polarization or by using the convolution method. However, PWIA does not account for nuclear effects such as Final State Interactions and Meson Exchange Currents which are known to be increasingly important at low $Q^2$. EMC effects are also not included. Furthermore, Pauli blocking is not included in PWIA and it should play an important role at low $Q^2$, which may explain the striking result of experiment E94010 which shows a large positive trend of the GDH sum on $^3$He at low $Q^2$, while the sum rule at the photon point has a large negative value (-498 $\mu$barn) (see fig. 8) [113]. The increasing complexity of the extraction at low $Q^2$ is reflected in the uncertainty of the PWIA which is estimated to range from 5% at large $Q^2$ to 10% at $Q^2 = 0.1$ GeV$^2$. This estimate is obtained by comparing the PWIA and effective polarization results and assuming that the difference is representative of the neutron extraction uncertainty. Although accounting for nuclear effects appears to be difficult at low $Q^2$, there is on-going work to include final state interactions in the PWIA model [114].

## A.2 Deuterium

In the DIS limit, a convolution method based on the impulse approximation is also used to extract the neutron from the deuteron [96]. The electron-nucleon scattering amplitude is convoluted with the wave function of the nucleon inside the deuteron. The most important nuclear effects, for SSF in DIS, are Fermi-motion and the D-Wave depolarization effect. The convolution can be expressed as:

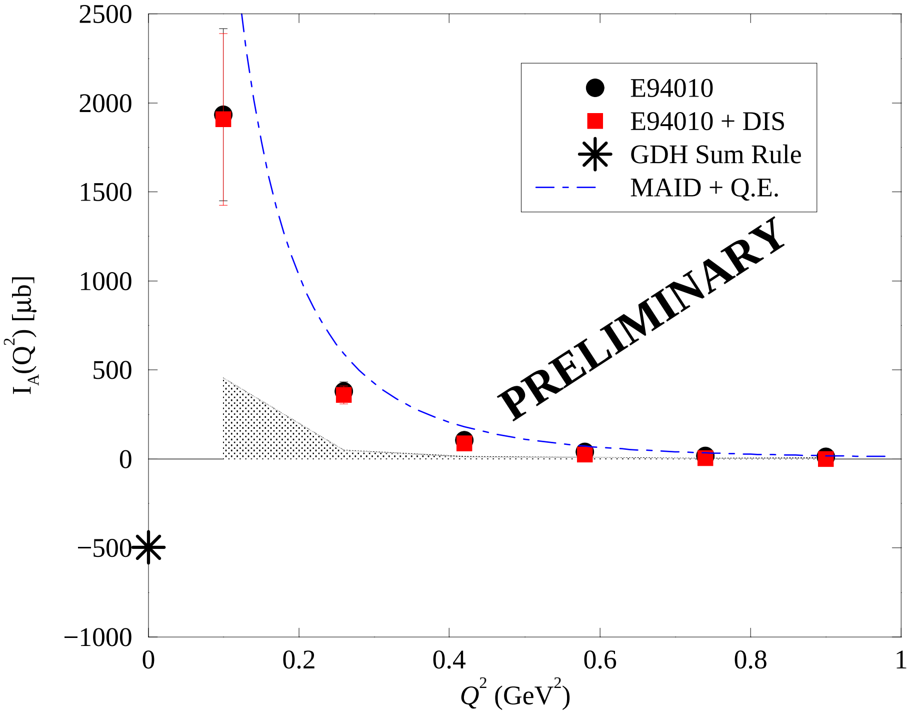


Figure 8: Preliminary results on the generalized GDH sum on $^3$He.

$$g_1^D(x, Q^2) = \int_x^{M_D/m} \frac{dy}{y} g_1^N(x/y, Q^2) \overrightarrow{f_D}(y) \tag{7}$$

where $\overrightarrow{f_D}(y)$ is the "spin dependent effective distribution of the nucleons" and $g_1^N = (g_1^p + g_1^n)/2$. $\overrightarrow{f_D}(x)$ has a sharp maximum at $y \simeq 1.0$ and is normalized to (1-1.5$\omega_D$), leading to the usual approximate formula:

$$g_1^D = \frac{1}{2}(g_1^p + g_1^n)(1 - 1.5\omega_D) \tag{8}$$

with $\omega_D \simeq 0.05$ from N-N potential calculations. Eq. 8 becomes an exact consequence of Eq. 7 if moments are considered.

At finite $Q^2$ and $\nu$, the integration limit of eq. 7 and $\overrightarrow{f_D}(y)$ become $x$-dependent, so in principle Eq. 8 does not hold. In practice, corrections are small (0.3% effect at $Q^2$=1 GeV$^2$).

Just like for $^3$He, the simple Eq. 8 is not reliable in the resonance region due to Fermi smearing, but can be used to a good approximation for moments, as long as $Q^2$

is not too small. The change in normalization of $\overrightarrow{f_D}(y,x,Q^2)$ with respect to $\overrightarrow{f_D}(y)$ leads to a correction term $N_f(Q^2)$:

$$g_1^D = \frac{1}{2}(g_1^p + g_1^n)(1 - 1.5\omega_D)N_f(Q^2) \tag{9}$$

that can be interpreted as the effective number of nucleons seen by the virtual photon. The correction $N_f(Q^2)$ grows at low $Q^2$: $N_f(Q^2 \to \infty) = 1$, $N_f(Q^2 = 1) = 0.997$ and $N_f(Q^2 = 0.1) = 1.02$ [96].

As for $^3He$, nuclear effects in deuterium, such as final state interactions, that are known to be important at low $Q^2$ from unpolarized data, are not included in the extraction model. Given the large number of theory groups involved in these topics, deuterium data available at low $Q^2$ should push the calculations beyond the present approximations.

# References


[1] JLab E97-110. J.P. Chen, A. Deur and F. Garibaldi spokespersons.

[2] H. Arenhovel, A. Fix and M. Schwamb, arXiv:nucl-th/0409015.

[3] F. E. Low, Phys. Rev. **96**, 1428 (1954).

[4] M. Gell-Mann and M. L. Goldberger, Phys. Rev. **96**, 1433 (1954).

[5] M. Gell-Mann, M. L. Goldberger and W. E. Thirring, Phys. Rev. **95**, 1612 (1954).

[6] S. Gerasimov. Yad. Fiz. 2 598 (1965). S. D. Drell and A. C. Hearn. Phys. Rev. Lett. 16 908 (1966).

[7] S. Bass. Z. Phys. A. 355. 77 (1996)

[8] H. Arenhoevel, Phys. Lett. B **595**, 223 (2004)

[9] Ahrens *et al*. Phys. Rev. Lett. 87, 22003 (2001)

[10] K. Helbing, in Proceedings of the 3rd international symposium on the GDH sum rule and its extension. World Scientific. S. Kuhn and J.P. Chen editors.

[11] JLAB E04-102. D. Crabb, M. Khandaker, D. Sober spokepersons.

[12] http://www.legs.bnl.gov/

[13] SLAC proposal E-159. P.E Bosted and D. Crabb spokespersons.

[14] M. Anselmino, B.L. Ioffe and E. Leader, Sov. J. Nucl. Phys. 49, 136, (1989).

[15] J. D. Bjorken, Phys. Rev. **148**, 1467 (1966).

[16] D. Drechsel *et al.* Phys. rev. D63 114010 (2001).

[17] X. Ji and J. Osborn. J. Phys G27 127 (2001).

[18] SMC collaboration. Phys. Rev. D58 112001 (1998)

[19] E143 collaboration. Phys. Rev. Lett. 78. 815. (1997)

[20] HERMES collaboration. Phys. Lett. B444 531 (1998).

[21] Amarian *et al*. (the GDH E94010 collaboration). Phys. Rev. Lett. 89 242301 (2002).

[22] K. Slifer *et al.*. (the GDH E94010 collaboration). In preparation.

[23] R. Fatemi *et al.*, Phys. Rev. Lett. 91, 222002 (2003).

[24] J. Yun *et al.*, Phys. Rev. C 67, 055204 (2003).

[25] G.E Dodge, in Proceedings of the Third International Symposium on the GDH Sum Rule and its Extension. World Scientific. S.E. Kuhn and J.P. Chen editors, pg. 62 (200).

[26] JLab E03-006 M. Ripani, M. Battaglieri, A. Deur and R. deVita spokespersons.

[27] V. D. Burkert, Phys. Rev. D 63, 097904 (2001).

[28] C. Ciofi degli Atti, L. P. Kaptari, S. Scopetta and A. Y. Umnikov, Phys. Lett. B **376**, 309 (1996)

[29] 2003 Hall A Status report, p58, http://hallaweb.jlab.org/publications/StatusReports/StatusReport2003.ps

[30] M. Amarian *et al.* Phys. Rev. Lett. 93 152301 (2004)

[31] V. Bernard, N. Kaiser, U-G. Mei$\beta$ner. Phys.Rev. D48 (1993) 3062-3069 ; V. Bernard, T. R. Hemmert, U-G. Mei$\beta$ner. hep-ph/0203167 (2002)

[32] X. Ji, J. Osborne. J. Phys. G27 (2001) 127 ; X. Ji, C-W Kao, J. Osborne. Phys.Rev. D61 (2000) 074003

[33] J. Soffer and O. V. Teryaev, Phys. Lett. B **545**, 323 (2002) [arXiv:hep-ph/0207252].

[34] http://isnwww.in2p3.fr/graal/graal_anglais.html

[35] http://www.spring8.or.jp/

[36] http://www.tunl.duke.edu/~capture/

[37] A. Deur *et al.* Phys Rev Lett. 93 212001 (2004)

[38] F. Xiong *et al.*, Phys. Rev. Lett. **87**, 242501 (2001)

[39] R. Gilman, Nucl. Phys. A **737**, 156 (2004).

[40] Meissner, personal communication.

[41] C. D. Keith *et al.*, Nucl. Instrum. Meth. A **501**, 327 (2003).

[42] B. A. Mecking *et al.* [CLAS Collaboration], Nucl. Instrum. Meth. A **503**, 513 (2003).

[43] Hall B model. S. Kuhn, private communication.

[44] Vipuli Dharmawardane, personal communication.

[45] L. W. Mo and Y. S. Tsai, Rev. Mod. Phys. **41**, 205 (1969).

[46] I. V. Akushevich and N. M. Shumeiko, J. Phys. G **20**, 513 (1994).

[47] V. D. Burkert and B. L. Ioffe, Phys. Lett. B **296**, 223 (1992).

[48] M. Amarian *et al.* [Jefferson Lab E94-010 Collaboration], Phys. Rev. Lett. **92**, 022301 (2004) [arXiv:hep-ex/0310003].

[49] E. Thomas and N. Bianchi, Nucl. Phys. Proc. Suppl. **82**, 256 (2000).

[50] C. Ciofi degli Atti and S. Scopetta. Phys. Lett. B404 223 (1997)

[51] JLab Experiment E94-017. W. K. Brooks and M. F. Vineyard. See e.g. nucl-ex/0504028

[52] J. Bermuth *et al.*, Phys. Lett. **B564** 199 (2003)

[53] R. Schiavilla and I. Sick. Phys. Rev. **C64** 041002 (2001)

[54] I. Passchier *et al.*, Phys. Rev. Lett. **82** 4988 (1999)

[55] M. Ostrick *et al.*, Phys. Rev. Lett. **83**, 276 (1999)

[56] C. Herberg *et al.*, Eur. Phys. J. **A5** 131 (1999)

[57] H. Zhu *et al.*, Phys. Rev. Lett. **87** 081801 (2001)

[58] A. Lung *et al.*, Phys. Rev. Lett. **68** 3841 (1992); P. Bosted *et al.*, Phys. Rev. Lett. **70** 718 (1993)

[59] H. Gao *et al.*, Phys. Rev. **C50** R546 (1994)

[60] W. Xu *et al.*, Phys. Rev. Lett. **85** 2900 (2000); Phys. Rev. **C 67**, 012201(R) (2003)

[61] W. Bartel *et al.*, Nucl. Phys. **B58** 429 (1973)

[62] P. Markowitz *et al.*, Phys. Rev. **C48** R5 (1993)

[63] T. Eden *et al.*, Phys. Rev. **C50** 1749 (1994)

[64] H. Anklin *et al.* Phys. Lett. **B336** 313 (1994)

[65] H. Anklin *et al.* Phys. Lett. **B428** 248 (1998)

[66] E. E. W. Bruins *et al.* Phys. Rev. Lett. 75 21 (1995)

[67] G. Kubon *et al.*, Phys. Lett. **B524** 26 (2002)

[68] S. Galster *et al.*, Nucl. Phys. **B32** 221 (1971)

[69] S. Platchkov *et al.*, Nucl. Phys. **A510** 740 (1990)

[70] M. Meyerhoff *et al.*, Phys. Lett. **B327** 201 (1994)

[71] J. Becker *et al*., Eur. Phys. J. **A6**, 329 (1999)

[72] JLab E02-013 B. Wojtsekhowski *et al*.

[73] R. Madey *et al.*, Phys. Rev. Lett. **91** 122002 (2003)

[74] JLab E04-110 R.Madey *et al*.

[75] D.I. Glazier *et al.*, Eur. Phys. J. **A24** 101 (2005)

[76] E143 collaboration: K. Abe *et al.*, E143 collaboration, Phys. Rev. **D58** 112003 (1998)

[77] SMC collaboration: D. Adeva *et al.*, Phys. Rev. **D58** 112001 (1998).

[78] HERMES collaboration: A. Airapetian *et al.*, Eur. Phys. J. **C26**, 527 (2003).

[79] HERMES collaboration: K. Ackerstaff *et al.*, Phys. Lett. **B444** 531 (1998)

[80] E155 collaboration: P. L. Anthony *et al.*, Phys. Lett. **B493** 19 (2000)

[81] CLAS collaboration: J. Yun *et al.*, Phys. Rev. **C 67** 055204 (2003)

[82] JLab experiment E03-109, S. Choi, Z. E. Meziani and O. Rondon spokespersons

[83] G. Dodge. Proceedings of the GDH 2004 Workshop. World Scientific. S. Khun and J-P Chen editors. 2005.

[84] JLab Experiment E-01-006. O. Rondon and M. Jones spokespersons.

[85] E142 collaboration: P.L. Anthony *et al.*, Phys. Rev. **D54** 6620 (1996)

[86] E154 collaboration: K. Abe *et al.*, Phys. Rev. Lett. **79** 26 (1997)

[87] E154 collaboration: K. Abe *et al.*, Phys. Lett. **B404** 377 (1997)

[88] X. Zheng *et al.*, Phys. Rev. **C70** 065207(2004)

[89] M. Amarian *et al.*, Phys. Rev. Lett. **89** 242301 (2002)

[90] JLab experiment E01-012 N. Liyanage, J-P Chen, Seonho Choi spokespersons.

[91] K. Kramer *et al.*, nucl-ex/0506005.

[92] JLab experiment E97-110 J-P Chen, A. Deur, F. Garibaldi spokespersons.

[93] J. Friar et al. Phys. Rev. **C42**. 2310.(1990)

[94] C. Ciofi degli Atti and S. Scopetta, E Pace, G. Salmè. Phys. Rev. C **48** 968. (1993)

[95] C. Ciofi degli Atti and S. Scopetta. Phys. Let. B**404** 223, (1997)

[96] C. Ciofi degli Atti, S. Scopetta, A.Yu. Umnikov and L.P. Kaptari. Phys. Lett. **376** 309 (1996)

[97] S.A. Kulagin, W. Melnitchouk, G. Piller, W. Weise; Phys. Rev. **C52** 932 (1995)

[98] G.Piller, W.Melnitchouk, A.W.Thomas Phys. Rev. **C54** 894 (1996)

[99] M. Lacombe *et al*, Phys. Rev. **C21** 861 (1980)

[100] R. Machleidt, K. Holinde and C. Elster, Phys. Rept. 149 1 (1987)

[101] M. J. Zuilhof and J. A. Tjon Phys, Rev. **C22** 2369 (1980)

[102] K. Kotthoff, R. Machleidt and D. Schutte, Nucl. Phys. **A264** 484 (1976)

[103] B. Desplanques, Phys. Lett. **B203** 200 (1988)

[104] L.P. Kaptari and A.Yu. Umnikov, Phys. Lett. **B240** 203 (1990)

[105] L.P. Kaptari, A.Yu. Umnikov, C. Ciofi degli Atti, S. Scopetta, and K.Yu. Kazakov, Perugia Report No. DFUPG 92/94 (1994)

[106] L.L. Frankfurt and M.I. Strikman, Nucl. Phys. **A405** 557 (1983)

[107] R.M. Woloshyn, Nucl. Phys. **A496** 749 (1989)

[108] L.P. Kaptari, K.Yu. Kazakov, A.Yu. Umnikov and B. KÃd'mpfer, Phys. Lett. **B321** 271 (1994)

[109] M.V. Tokarev, Phys. Lett. **B318** 559 (1993)

[110] W. Melnitchouk, G. Piller and A.W. Thomas, Phys. Lett. **B346** 165 (1995)

[111] A.Yu. Umnikov, L.P. Kaptari, K.Yu. Kazakov, and F.C. Khanna, Alberta Report No. Thy 29 94 (1994).

[112] I.R. Afnan *et al*. Phys. Lett. **B493** 36 (2000); Phys. Rev. **C68** 035201 (2003)

[113] K. Slifer, proceedings of the GDH 2004 Workshop. World Scientifi c, S. Kuhn and J-P Chen editors (2005)

[114] A. Kievsky , E. Pace, G. Salm\'{e}; proceedings of the GDH 2004 Workshop. World Scientifi c, S. Kuhn and J-P Chen editors (2005)